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(54) **ULTRASOUND PROBE WITH DYNAMIC FOCUS AND ASSOCIATED SYSTEMS AND METHODS**

(71) Applicant: **General Electric Company**, Schenectady, NY (US)

(72) Inventors: **Scott D. Cogan**, Niskayuna, NY (US); **Shinichi Amemiya**, Tokyo (JP); **Bruno Hans Haider**, Niskayuna, NY (US); **Geir Ultveit Haugen**, Oslo (NO)

(73) Assignee: **General Electric Company**, Niskayuna, NY (US)

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G01S 15/89	(2006.01)
G10K 11/34	(2006.01)

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CPC *G01S 7/5208* (2013.01); *G01S 15/8927* (2013.01); *G10K 11/346* (2013.01); *G01S 7/52095* (2013.01)

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USPC 367/138
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(56) **References Cited**

U.S. PATENT DOCUMENTS

4,969,132	A	11/1990	Reed
5,817,024	A	10/1998	Ogle et al.
5,964,709	A	10/1999	Chiang et al.
6,471,650	B2	10/2002	Powers et al.
6,582,369	B1	6/2003	Huang et al.
6,926,671	B2	8/2005	Azuma et al.
7,527,592	B2	5/2009	Haugen et al.

(Continued)

FOREIGN PATENT DOCUMENTS

EP	1491913 A2	12/2004
EP	2284566 A1	2/2011
WO	2007039972 A1	4/2007

OTHER PUBLICATIONS

Azar et al., "Beam Focusing Behavior of Linear Phased Arrays", NDT & E International, vol. 33, Issue 3, pp. 189-198, Apr. 2000.

(Continued)

Primary Examiner — Mark Hellner

(74) *Attorney, Agent, or Firm* — Seema S. Katragadda

(57) **ABSTRACT**

Exemplary ultrasound probes with sub-aperture processing capable of dynamic focus are provided that generally include an array of transducer elements that form a sub-aperture in the ultrasound probe. The transducer elements can be assigned to dynamic delay update groups and an initial delay can be applied to ultrasound signals associated with the transducer elements of the sub-aperture. A sub-aperture processor can be configured to dynamically apply delay updates to the ultrasound signals associated with the transducer elements of the sub-aperture according to the dynamic delay update groups to which the transducer elements are assigned. Exemplary ultrasound systems with a dynamic focus and methods of transmitting ultrasound signals with a dynamic focus are also provided.

22 Claims, 9 Drawing Sheets
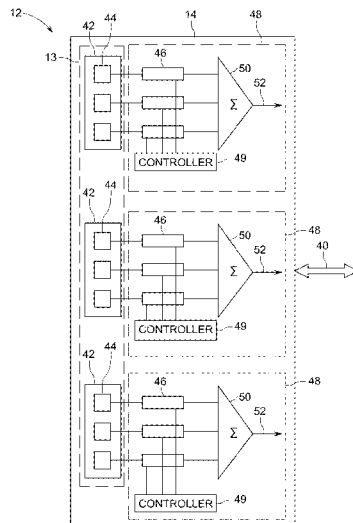
(56)   **References Cited**

U.S. PATENT DOCUMENTS

7,635,334	B2	12/2009	Phelps	
8,177,718	B2	5/2012	Savord	
2002/0045823	A1	4/2002	Fraser	
2005/0243812	A1*	11/2005	Phelps	370/360
2006/0116580	A1*	6/2006	Fukukita	600/447
2010/0298714	A1	11/2010	Miyajima	
2012/0083695	A1	4/2012	Napolitano et al.	
2012/0095344	A1	4/2012	Kristoffersen et al.	

OTHER PUBLICATIONS

Li et al., "Efficient Dynamic Focus Control for Three-Dimensional Imaging Using Two-Dimensional Arrays", IEEE Transactions onUltrasonics, Ferroelectrics and Frequency Control, vol. 49, Issue 9, pp. 1191-1202, Sep. 2002.

Brunner, "How Ultrasound System Considerations Influence Front-End Component Choice", Analog Dialogue, Inc., 36-03, 2002, available at http://www.analog.com/library/analogDialogue/archives/36-03/ultrasound/ultrasound.pdf.

Blaak et al., "Design of a Micro-Beamformer for a 2D Piezoelectric Ultrasound Transducer", IEEE International Ultrasonics Symposium (IUS), pp. 1338-1341, Sep. 20-23, 2009, Location: Rome.

Palmese et al., "An Efficient Digital CZT Beamforming Design for Near-Field 3-D Sonar Imaging", IEEE Journal of Oceanic Engineering, vol. 35, Issue 3, pp. 584-594, Jul. 2010.

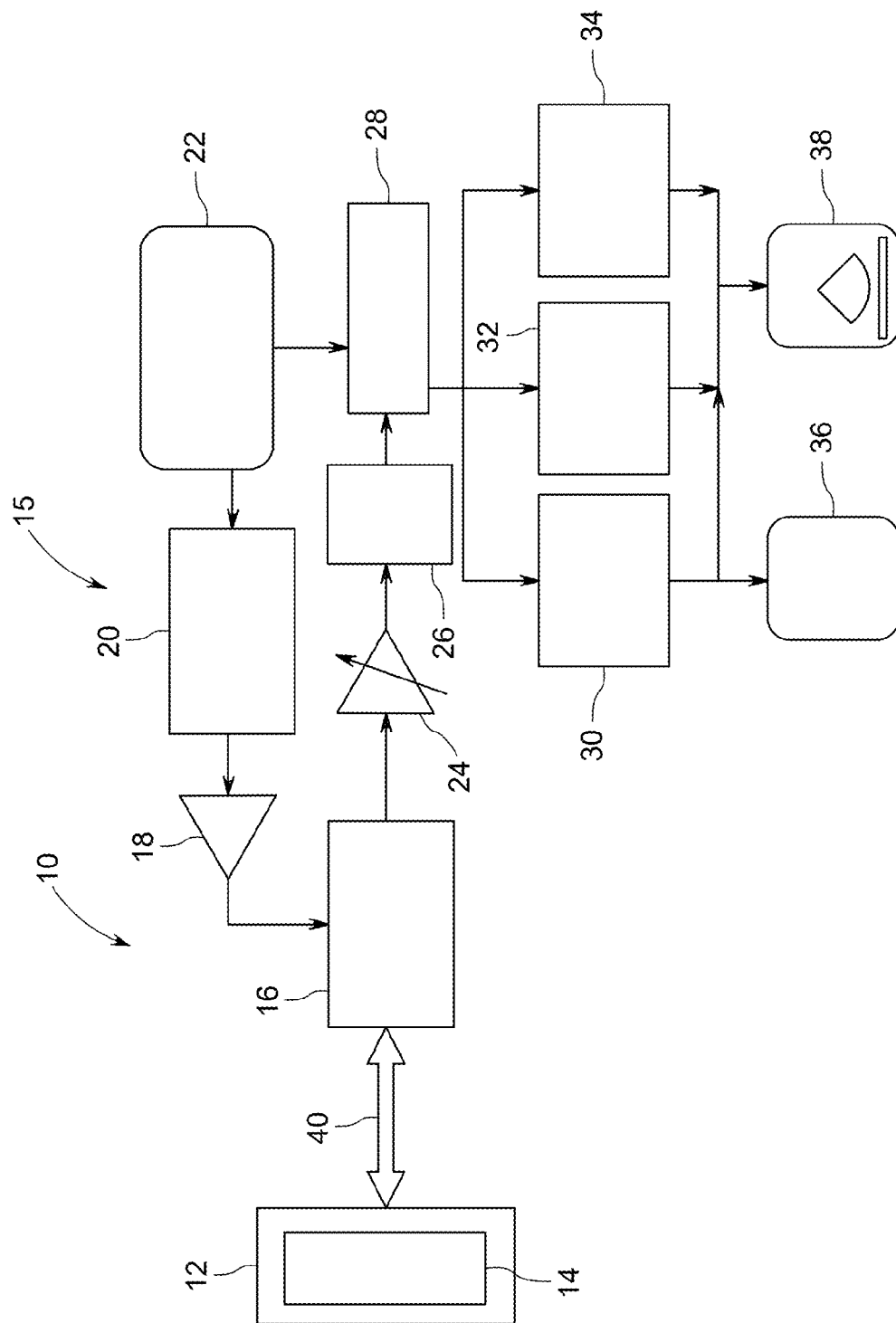PCT Search Report and Written Opinion issued in connection with corresponding Application No. PCT/US2014/036574 on Aug. 8, 2014.
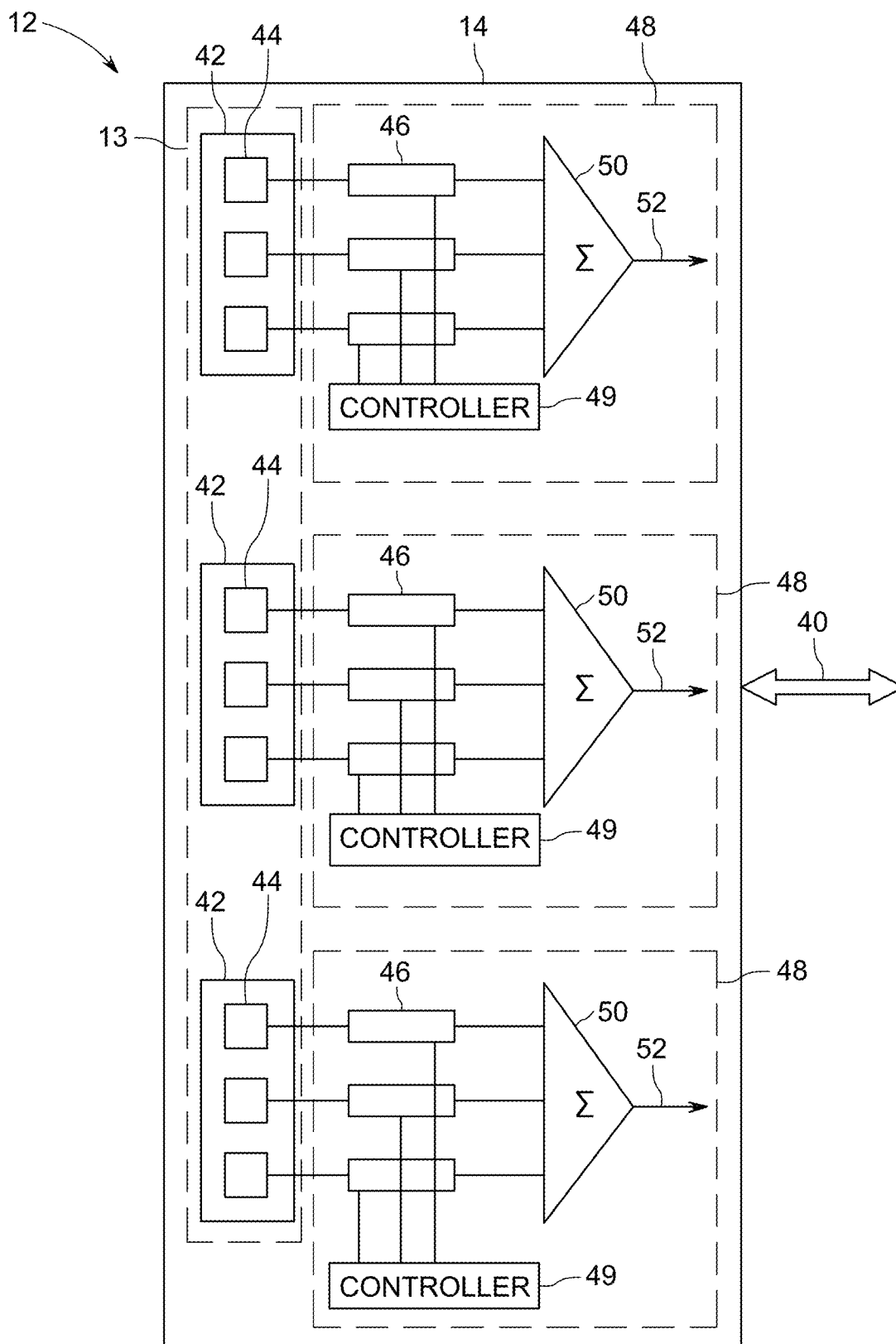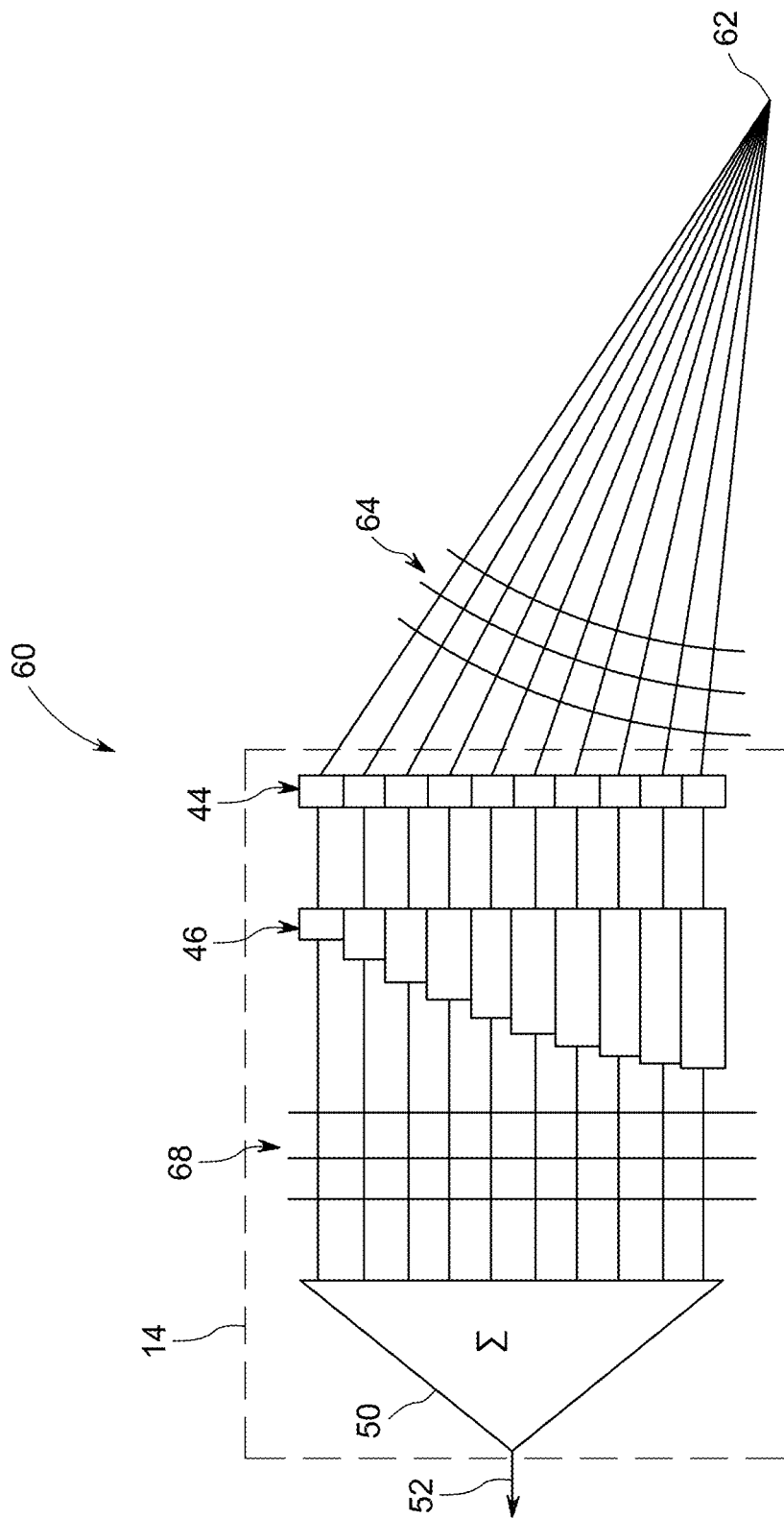
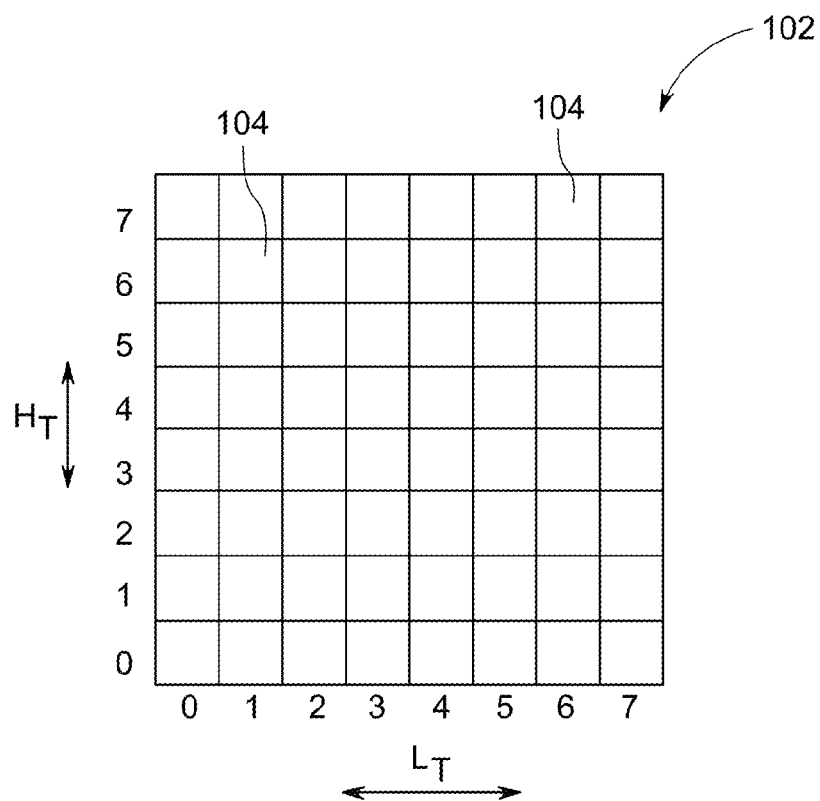* cited by examiner

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIG. 6

200

202

5	A	B	C	D	E
4	A	B	C	D	E
3	A	B	C	D	E
2	A	B	C	D	E
1	A	B	C	D	E

204

FIG. 7A

200'

202'

204'

A	A	B	B	C
A	B	B	C	D
B	B	C	D	D
B	C	D	D	E
C	D	D	E	E

204'

204'

204'

204'

204'

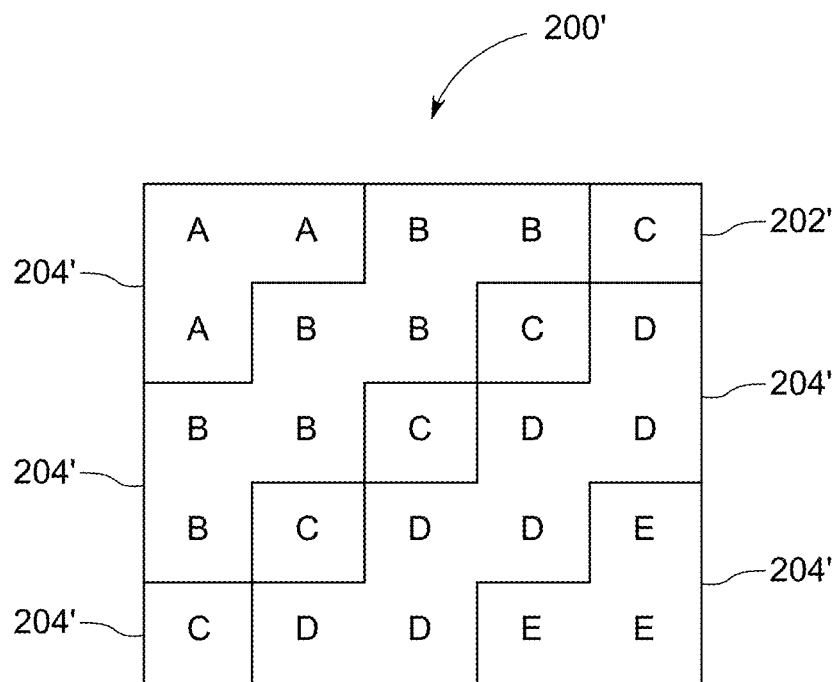## FIG. 7B

FIG. 8

FIG. 9

250

252
START

254
STOP

256
RATE

FIG. 10

------ (a) SAP NEAR THE
            EDGE OF ARRAY

-·-·-·- (b) SAP NEAR THE
            CENTER OF ARRAY
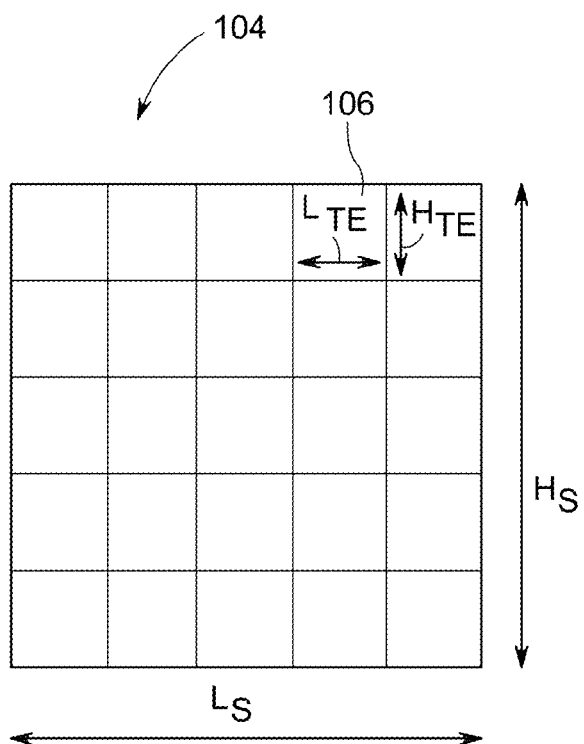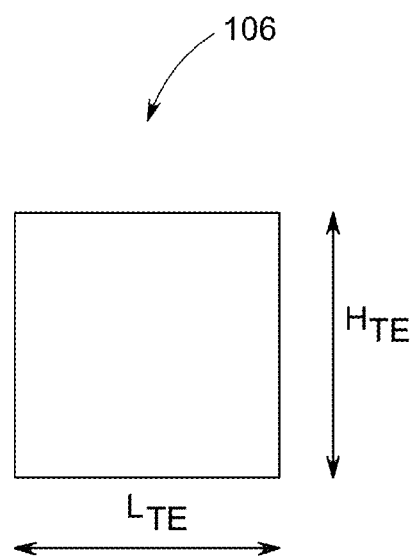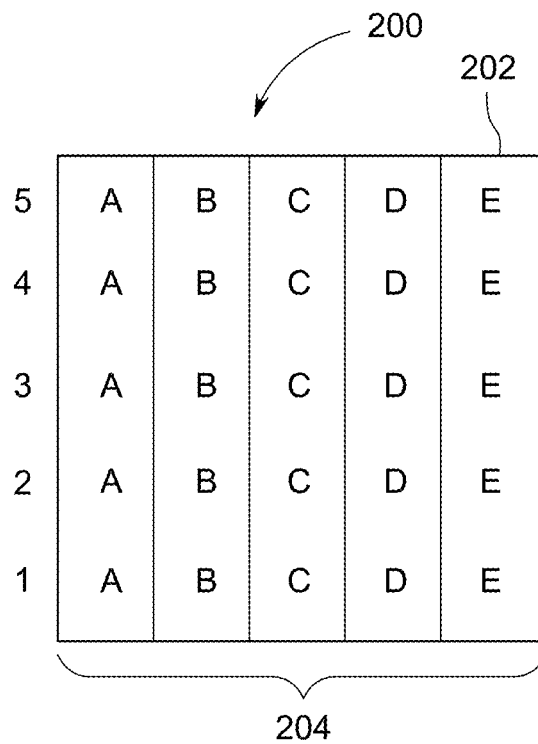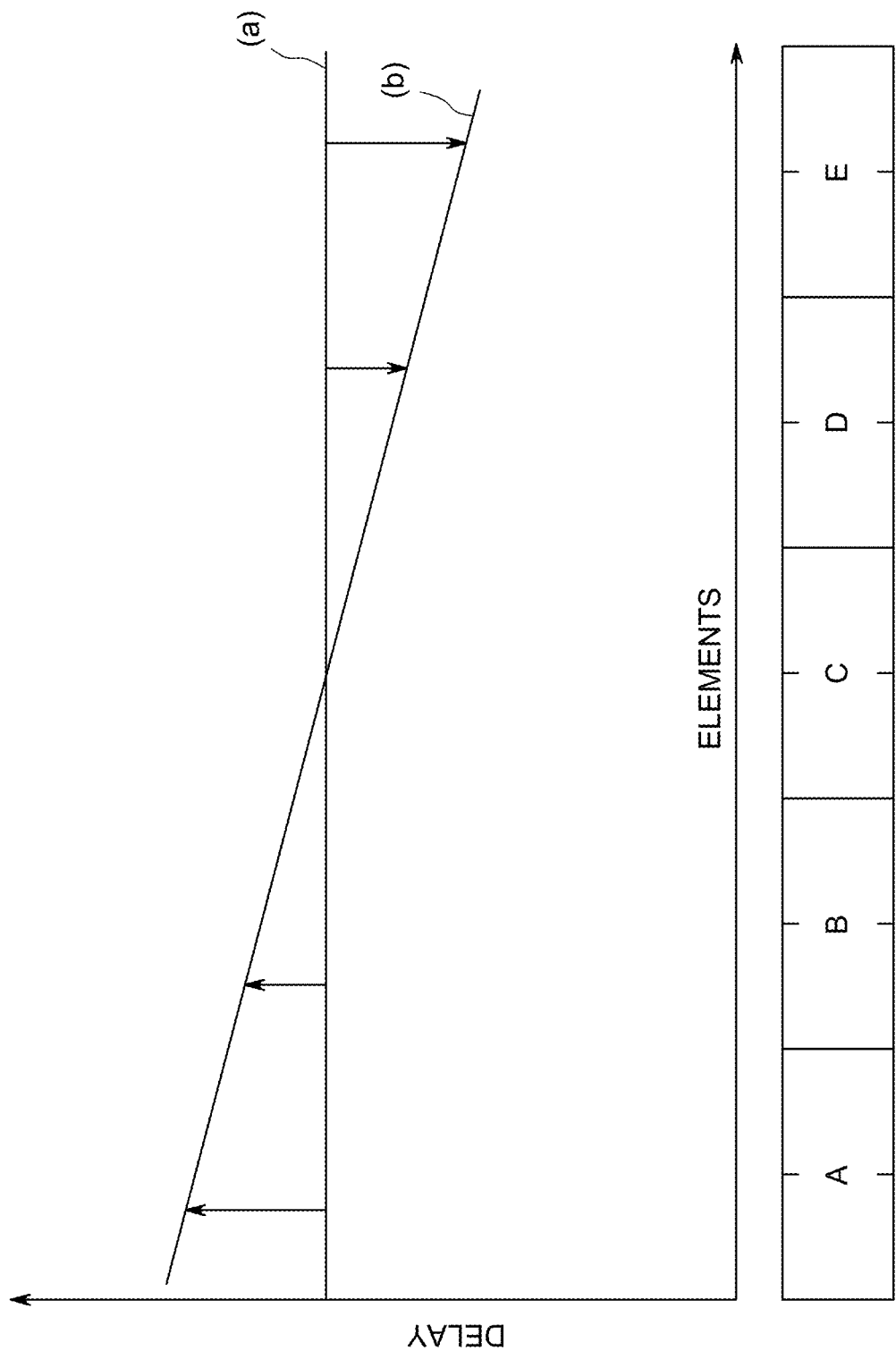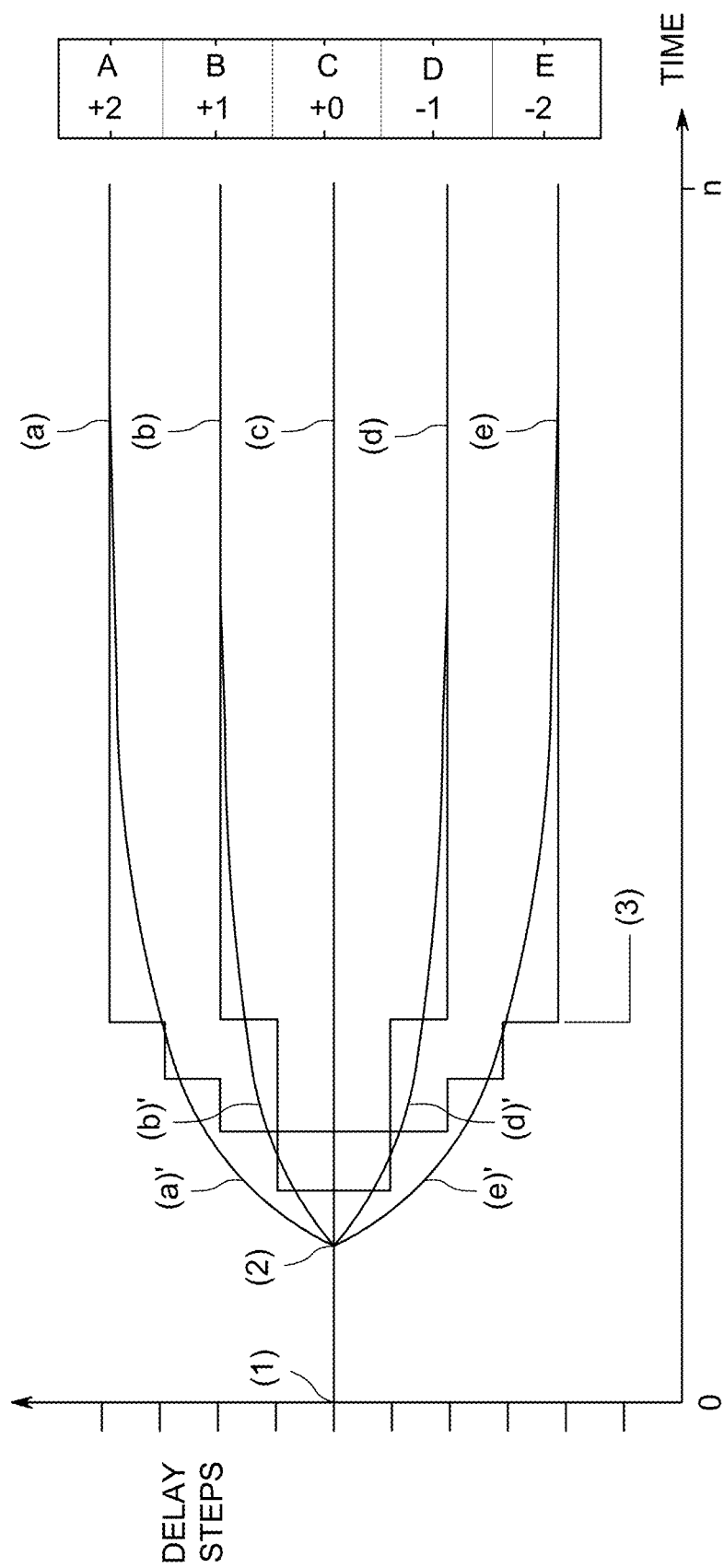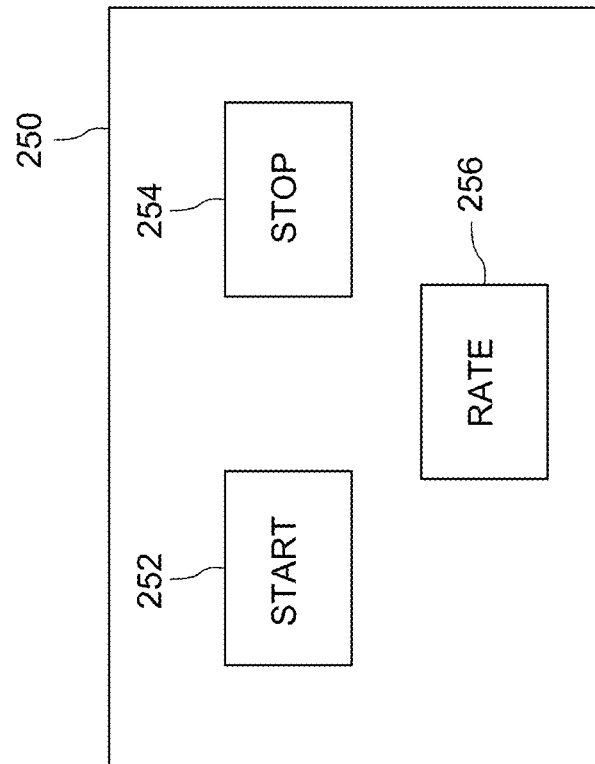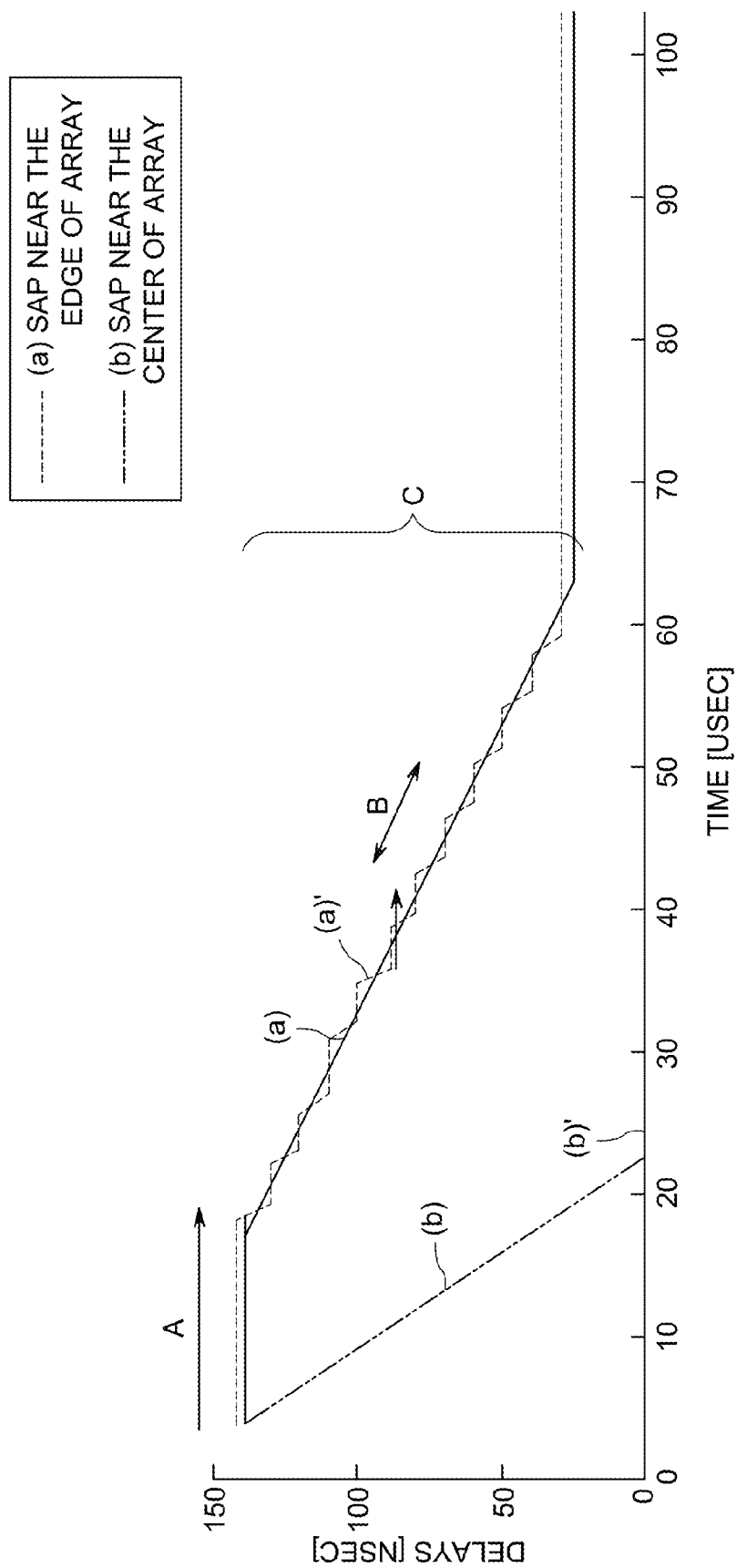
FIG. 11

ULTRASOUND PROBE WITH DYNAMIC FOCUS AND ASSOCIATED SYSTEMS AND METHODS

TECHNICAL FIELD

The present disclosure relates to ultrasound probes and associated systems and methods and, in particular, to ultrasound probes with sub-aperture beamforming and dynamic focus with a simplified dynamic delay updating mechanism.

BACKGROUND

Conventional ultrasound systems generally include an ultrasound probe formed from a plurality of transducers which define an aperture of the ultrasound probe. The transducers can be arranged spatially and can be divided into a plurality of sub-apertures or sub-arrays. Sub-aperture processors (SAPs) may perform beamforming operations for the elements within the sub-aperture, on both transmit and/or receive operations. A typical ultrasound system generally further includes a receive and/or transmit beamformer that is external to the probe and that is connected to the transducer elements by electrical cables.

The beamformer generally focuses and steers ultrasound energy transmitted and received by the probe to acquire acoustic reverberation data as one step in generating images of anatomic content on a display. In particular, the transmit beamformer generates pulse or continuous signals and the plurality of transducers convert electrical signals to pressure waves and vice versa. The pressure waves generally propagate through tissue and part of the ultrasound energy is reflected back to the transducers. The receive beamformer processes the received ultrasound echoes and focuses the energy. The ultrasound signals are then processed and converted into an audio output and/or a visual display at a graphical user interface (GUI).

As described above, each ultrasound waveform is output by the probe via a respective channel. In conventional (non-3D) ultrasound systems, each transducer element is normally associated with a distinct cable or wire connecting the probe to the beamformer to facilitate processing of the respective ultrasound signal, e.g., geometrical calculations are required for each transducer element for steering. For 3D ultrasound systems with thousands of individual elements, a distinct cable is not feasible. To deal with the thousands of elements, transmission is handled by distribution of a set of transmit signals from the system or with transmitters in the probe. Receiving is handled with a combination of beamforming in the probe and/or system. The probe beamforming can be analog and/or digital. A digital solution requires an analog-to-digital (ADC) converter in the probe. Since each channel can have an ADC, some implementations can require thousands of ADCs. As a result, the implementation of a beamformer in the probe may require one or a plurality of application specific integrated circuits (ASIC) and a technical solution that makes it possible to fit the circuitry needed within the required restrictions on silicon area, power, setup data, calculation time, and the like.

Thus, a need exists for ultrasound probes with means for reducing the complexity for implementing a dynamic beamformer. These and other needs are addressed by the ultrasound probes and associated systems and methods of the present disclosure.

SUMMARY

In accordance with embodiments of the present disclosure, exemplary ultrasound probes with sub-aperture processing

capable of dynamic focus are provided that generally include groups or arrays of transducer elements that form sub-apertures in the ultrasound probe. The transducer elements of the sub-apertures can transmit and/or receive ultrasound signals. An initial delay can generally be applied to ultrasound signals associated with the individual transducer elements of the sub-apertures. The exemplary ultrasound probes generally include a sub-aperture processor configured to dynamically apply delay updates to the ultrasound signals associated with the transducer elements of the sub-apertures. In order to simplify the implementation, the transducer elements can be assigned to one out of a plurality of dynamic delay update groups, where transducer elements within an update group can apply the same delay updates at the same delay updates at the same rate and/or magnitude. The sub-aperture processor can therefore be configured to dynamically apply delay updates to the ultrasound signals repeatedly for a predetermined time period to approximate an ideal delay profile, with the frequency of the delay updates being configurable per sub-aperture processor and the magnitude of the delay updates being dependent on the dynamic delay update groups to which the transducer elements are assigned.

The sub-aperture processor can assign the transducer elements to the plurality of dynamic update groups by configuring the sub-aperture processor to apply a first delay modification to a first group of transducer elements within the sub-apertures and a second delay modification to a second group of transducer elements within the sub-apertures. This process can be repeated for the plurality of dynamic update groups. The delay modifications of each delay update group can be different from the delay modification of the other delay update groups. A delay modification of the delay update group can have an opposite sign of a delay modification of another delay update group. One or more of the delay update groups may not receive a delay modification. In some exemplary embodiments, the delay modifications can be static.

The dynamic delay update groups within the sub-apertures can be updated at two or more different rates. Alternatively, the delay updates may be applied at the same rate, but using two or more different delay update magnitudes. The delay updates applied by the sub-aperture processor can be a curved or piecewise linear approximation of an ideal delay profile associated with the transducer elements in the dynamic delay update groups. The sub-aperture processor can be configured to apply the initial delay to the ultrasound signals to substantially align the phase of the ultrasound signals initially received by the sub-aperture elements. The sub-aperture processor can be further configured to apply delay updates to the dynamic delay update groups to substantially align the ultrasound signals received by the transducer elements in phase for the sub-aperture as a function of time.

The sub-aperture processor can be configured for processing of a plurality of beams. For example, the sub-aperture process can be configured to process a first beam with a first set of dynamic delay update parameters and a second beam with a second set of dynamic delay update parameters. The first set of dynamic delay update parameters can be different from the second set of dynamic delay update parameters, and the delay update group assignments may also be different form one beam to the next. To process a first beam direction, the sub-aperture processor can be set up in accordance with the above-described scheme to beamform the ultrasound signals from the direction of the first beam. To process a second beam direction, the sub-aperture processor can be set up in accordance with the above-described scheme to beamform the ultrasound signals from the direction of second beam. In some embodiments, rather than being connected to the trans-

ducer elements directly, the receive beamformer can be connected to the sub-aperture processor electronics. This exemplary set-up can be repeated for each beam in the plurality of beam directions. The sub-aperture processor can be further configured to set a rate for applying discrete delay updates to ultrasound signals associated with the transducer elements of the sub-apertures. Further, the sub-aperture processor can be configured to set a magnitude of the initial delay applied to ultrasound signals associated with the transducer elements of the sub-apertures. The delay updates can be one of, e.g., an incremented delay, a static delay, a decremented delay, and the like.

The sub-aperture processor can be configured to apply a set of initial delays to ultrasound signals associated with the transducer elements of the sub-apertures. Further, the sub-aperture processor can be configured to begin applying the delay updates to ultrasound signals associated with the transducer elements of the sub-apertures in response to a counter, e.g., a start counter, and the like. In addition, the sub-aperture processor can be configured to continue applying delay updates at intervals specified by a counter, e.g., a rate counter, and the like. The sub-aperture processor can further be configured to stop applying the delay updates to ultrasound signals associated with the transducer elements of the sub-apertures in response to a counter, e.g., a stop counter, and the like. In some embodiments, the counter can be part of a controller. Although a counter is used in relation to sub-aperture control, it should be understood that in some embodiments, other types of control circuitry can be used.

In accordance with embodiments of the present disclosure, exemplary ultrasound systems with a dynamic focus are provided that include an ultrasound probe including an array or group of transducer elements that form a sub-aperture(s). The exemplary systems further include a sub-aperture processor configured to apply an initial delay to ultrasound signals associated with the transducer elements of the sub-apertures. The transducer elements of the sub-apertures can be assigned to dynamic delay update groups. The sub-aperture processor can be further configured to dynamically apply delay updates to the ultrasound signals repeatedly for a predetermined time period to approximate an ideal delay profile. The delay updates can be configurable per sub-aperture processor. A magnitude of the delay updates can be dependent on the dynamic delay update groups to which the transducer elements are assigned.

The sub-aperture processor generally includes at least one counter, e.g., a start counter, a rate counter, a stop counter, and the like. The sub-aperture processor can be configured to apply the initial delay to ultrasound signals associated with the transducer elements and apply delay updates in response to the at least one counter. The sub-aperture processor can be further configured to apply discrete delay updates to ultrasound signals associated with the transducer elements at a specific rate each time the at least one counter reaches a specified value and to stop the delay updates after a specified number of delay updates has been completed.

In accordance with embodiments of the present disclosure, exemplary methods of receiving and/or transmitting ultrasound signals with a dynamic focus are provided that generally include applying an initial delay to ultrasound signals associated with transducer elements of a sub-aperture disposed in an ultrasound probe. The methods generally include assigning the transducer elements of the sub-aperture to dynamic delay update groups. Further, the exemplary methods generally include applying delay updates to the ultrasound signals repeatedly for a predetermined time period to approximate an ideal delay profile. A frequency of the delay

updates can be configurable per sub-aperture processor. A magnitude of the delay updates can be dependent on the dynamic delay update group to which the transducer elements are assigned.

The exemplary methods can include transmitting ultrasound signals via the transducer elements of the sub-apertures and applying the initial delay to the ultrasound signals via a sub-aperture processor to specify a focal point or the desired focus information for the ultrasound signals. The exemplary methods further include receiving ultrasound signals via the transducer elements of the sub-apertures and applying the delay updates to the ultrasound signals via a sub-aperture processor to substantially align the ultrasound signals received by the transducer elements in phase for each of the dynamic delay update groups.

The exemplary methods can include processing a first beam using a first set of dynamic delay update parameters and a second beam using a second set of dynamic delay update parameters. The first set of dynamic delay update parameters can be different from the second set of dynamic delay update parameters. The exemplary methods generally include applying different delay increments or decrements for the delay updates for each of the first and second set of dynamic delay update parameters. Further, the exemplary methods include applying different delay update periods for the delay updates for each of the first and second set of dynamic delay update parameters. In general, the exemplary methods include setting a rate for discretely applying the delay updates to ultrasound signals associated with the transducer elements of the sub-apertures.

Other objects and features will become apparent from the following detailed description considered in conjunction with the accompanying drawings. It is to be understood, however, that the drawings are designed as an illustration only and not as a definition of the limits of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

To assist those of skill in the art in making and using the disclosed devices and associated systems and methods, reference is made to the accompanying figures, wherein:

FIG. 1 shows block diagrams of an exemplary ultrasound system;

FIG. 2 shows an exemplary block diagram of a ultrasound probe including sub-aperture processors to illustrate a receive mode of operation;

FIG. 3 shows a block diagram of an exemplary beamforming system;

FIG. 4 shows an exemplary transducer with a two-dimensional array of sub-apertures;

FIG. 5 shows an exemplary sub-aperture with a two-dimensional array of transducer elements;

FIG. 6 shows an exemplary transducer element;

FIGS. 7A and 7B show exemplary sub-apertures with an exemplary grouping into dynamic delay update groups;

FIG. 8 shows an exemplary delay profile for a sub-aperture with grouped transducer elements;

FIG. 9 shows an exemplary delay profile approximation with delay increments and decrements based on dynamic delay update groups;

FIG. 10 shows a block diagram of an exemplary delay update timing controller for a sub-aperture processor; and

FIG. 11 shows an exemplary ideal steering profile for two exemplary sub-aperture shapes.

DESCRIPTION OF EXEMPLARY EMBODIMENTS

FIGS. 1 and 2 show an exemplary ultrasound system 10 of the present disclosure. Referring to FIG. 1, the system 10

generally includes an ultrasound probe **12** that includes an aperture assembly **14** formed from a plurality of transducer elements that define an aperture of the probe **12**. The main ultrasound processing unit **15** generally includes a transmit beamformer **20** connected to the transducer elements by electrical cables **40**. The system **10** can further include a high voltage transmit amplifier **18** (HV Tx AMP) for amplifying the transmit signals from the beamformer **20** and multiplexer/demultiplexer and transmit/receive switches **16** (MUX/DE-MUX and T/R switches). A beamformer central control system **22** can be utilized to control the beamformer **20**. The beamformer **20** can range from a pure setup/delay control to a full pulse transmitter depending on the chosen design.

The main ultrasound processing unit **15** can also include a time gain compensation amplifier **24** (TGC), an analog-to-digital converter **26** (ADC), and a receive beamformer **28** for receiving ultrasound energy signals. The received ultrasound signals can further be processed by, e.g., spectral Doppler processing **30**, image and motion processing **32**, color Doppler processing **34**, and the like. The transmit beamformer **20** generates pulse or control signals and the plurality of transducer elements convert electrical signals to pressure waves which propagate through tissue and reflect back to the transducer elements. The receive beamformer **28** processes the received ultrasound echoes and focuses the energy. The ultrasound signals are then processed and converted into an audio output **36** and/or a visual display **38** at a graphical user interface (GUI).

Referring now to FIG. **2**, the ultrasound probe **12** includes an aperture assembly **14** that is generally formed from a plurality of transducers elements **44** that define an aperture **13** of the probe **12**. The transducers elements **44** can be arranged spatially and may be divided into a plurality of sub-apertures **42** (SAs **42**) or sub-arrays for both transmit and receive operations. Each SA **42** of the transducer elements **44** can include a dedicated sub-aperture processor **48** (SAP **48**). The transducer elements **44** can individually receive an initial delay. In some embodiments, the transducer elements **44** can be grouped for receiving the same frequency and/or magnitude of a delay.

The sub-aperture processor **48** can be configured to regulate and/or control the application of delay elements **46** for example by dynamically controlling and/or applying initial delays, delay updates, and the like, to ultrasound signals received and output by the transducer elements **44** via a controller **49**. The delay elements **46** can be dynamically controlled and/or applied by the controller **49** to substantially align the phase of the ultrasound signals received by the transducer elements **44**. The dynamic processing of ultrasound signals by the controller associated with the transducer elements **44** occurs at the sub-aperture processor level of the exemplary aperture assembly **14**. A dedicated summation element **50** can be implemented in each SAP **48** to combine the plurality of phase-aligned ultrasound signals from the transducer elements **44** associated with a particular SAP **48** into a single ultrasound signal **52**, i.e., a single channel. The ultrasound signals **52** for each SA **42** can further be output from the probe **12** to a main ultra sound processing unit **15** via a cable **40**.

While FIG. **2** is illustrative of one exemplary embodiment, in which each SAP **48** can include a separate controller **49**, those skilled in the art will recognize that one controller **49** can be operatively coupled to each of the delay elements **46** in each of the SAPs **48**. Additionally, or in the alternative, the controller(s) **49** can be external to the probe **12**, and can, for example, be implemented within the main processing unit **15**.

FIG. **3** shows an exemplary beam **60** being received by an exemplary embodiment of one of the sub-apertures **42** and processed by an exemplary embodiment of the sub-aperture processor **48**. The transmit beamformer **20** generally generates spherical signals such that a spherical wave of ultrasound signals is generated which focuses at a particular point. Thus, the timing for each ultrasound signal is slightly different than the other ultrasound signals, which can be defined by an arc-shaped delay pattern of ultrasound signals. For example, as illustrated in FIG. **3**, pulses are initially generated by a beamformer **20** and reflected pulses are received by transducer elements **44** of the sub-aperture **44**. The transmitted ultrasound signals can be reflected from a particular focal point **62**. Waveforms **64** illustrate the arc-shaped delay patterns of the ultrasound signals prior to correction. Each reflected waveform **64** can be received by a respective transducer element **44** and apply the corresponding delay, e.g., an arc-shaped delay pattern, with delay elements **46**. The arc-shaped waveforms **64** of sub-aperture **42** can further be dynamically corrected, i.e., dynamically steered or focused, with delay elements **46** of the sub-aperture processor **48** at correction stage **68** to create a phased-aligned version of the waveforms **64**. The lineated waveforms **64** may further be summed by an exemplary embodiment of the summation element **50** at a summing stage and output as a single signal **52** to be processed. Thus, rather than implementing separate channels for each waveform **64** received by the transducer elements **44**, the waveforms **64** can be phase-aligned and summed for each SA **42** and transferred to main processing unit **15**.

FIG. **4** illustrates an exemplary aperture **102** that includes an 8×8 two-dimensional array of SAs **104** for one application-specific integrated circuit (ASIC). Although illustrated as an 8×8 array of SAs **104**, it should be understood that in some exemplary embodiments, the aperture **102** can include a variety of SA **104** arrays. The ASIC associated with aperture **102** may also include a periphery input/output region for communicating the ultrasound signals between the ultrasound probe and the ultrasound signal processing system (not shown), e.g., a computer, a processing device, and the like. In some exemplary embodiments, the transducer length L_T can be approximately 10 mm and the transducer height H_T can be approximately 10 mm. For other exemplary embodiments, the transducer length L_T and the transducer height H_T can depend on the desired aperture for the probe type in question and whether more than one ASIC is utilized to span the desired aperture.

FIG. **5** illustrates an exemplary SA **104** of the aperture **102**. In particular, the individual SA **104** includes a 2D array of transducer elements **106**. It should be noted that the use of "2D array" in this context refers to indexing of the SA elements. The physical transducer elements **106** can be located along any spatial surface in 3D. Although illustrated as a 5×5 array of transducer elements **106**, in some exemplary embodiments, the 2D array can be, e.g., 5×3, 5×6, 10×5, and the like. For the exemplary SA **104** of FIG. **5**, the SAP length L_S can be approximately 1.25 mm and the SAP height H_S can be approximately 1.25 mm. The SA **104** geometry can be selected such that a single ASIC can be implemented for a number of applications which span RX frequencies (i.e., receive frequencies) between, e.g., approximately 1 MHz and approximately 12 MHz, and the like, and support systems with channel counts between, e.g., approximately 16 channels and approximately 512 channels. For a full probe beamformer, the channel count can be as low as one. For example, in some exemplary embodiments, a 5×5 2D array of SAs **104** may be implemented with the option of combining multiple

SAs **104** together to create larger SAs **104** with different geometries. As described above, each SA **104** can include a dedicated sub-aperture processor for controlling the delays applied to the received ultrasound signals. Each sub-aperture processor thereby applies delays to transducer elements **44** associated with the respective sub-aperture processor. FIG. **6** shows an exemplary transducer element **106** of an SA **104**. An exemplary transducer element length L_{TE} can be approximately 250 μm and the transducer element height H_{TE} can be approximately 250 μm.

In exemplary embodiments, the ultrasound probe supports dynamic focusing, i.e., steering, for each sub-aperture using a sub-aperture processor within a beamforming ASIC. Dynamic focusing for the SAs **104** allows the sub-aperture processor to dynamically track the desired steering/focus along any receive beam vector in 3D. In particular, as will be described in greater detail below, the exemplary method of dynamic beamforming involves approximating the beamforming delays over the range of the beam and making incremental delay updates to reconfigurable groups of elements at specified intervals.

FIG. **7A** shows an exemplary SA **200** which includes a 5×5 2D array of transducer elements **202**. The exemplary methods include assigning the transducer elements **202** of the SA **200** to dynamic delay update groups **204**, e.g., groups A, B, C, D and E. Transducer elements **202** within the same delay update group **204** will receive the same delay updates for, e.g., a +20 nanosecond increment or a −20 nanosecond decrement at a certain time interval. Transducer elements **202** in some delay update groups **204**, e.g., group C, may have a static delay, and therefore do not receive any delay updates. Although illustrated as five dynamic delay update groups **204**, in some exemplary embodiments, any other number of dynamic delay update groups **204** may be implemented. The number of dynamic delay update groups **204** may depend on the SA **200** size. Ultrasound signals received by the respective transducer elements **202** can be sampled, delayed and/or summed within the sub-aperture processor for each SA **200**. Each sub-aperture processor applies an initial delay profile to the individual transducer elements **202** and the delays associated with each transducer element **202** can further be updated dynamically over time. In particular, the initial delay and the updated delays can be applied by the sub-aperture processor to delay elements that receive ultrasound signals from the transducer elements **202** to realize a dynamic updated steering/focusing direction. In some exemplary embodiments, the initial delay can be, e.g., approximately 10, 20, 30, and the like, nanoseconds. The delay elements associated with each of the transducer elements **202** of the SA **200** can be configured to support, e.g., a substantially similar initial delay, different initial delays, and the like. FIG. **7B** shows another exemplary SA **200'** which includes a 5×5 2D array of transducer elements **202'** which are assigned to dynamic delay update groups **205'**, e.g., groups A, B, C, D and E. Many different grouping patterns are possible, two of which are illustrated in FIGS. **7A** and **7B**.

While the ultrasound signals are received by the transducer elements **202**, the sub-aperture processor can apply delay updates, e.g., incremented delays, decremented delays, static delays, and the like, to the ultrasound signals associated with the transducer elements **202** based on the groups **204** to which the transducer elements **202** are assigned. The delay updates can be applied to substantially align in phase the ultrasound signals received by the transducer elements **202**. The steering update patterns indicate a direction, or rotary axis, about which the steering updates should be applied. The different update patterns can be approximated with a relatively small

number of possible grouping assignments in order to simplify the required circuitry. For example, sixteen different rotary axis patterns may be supported, two of which are shown in FIGS. **7A** and **7B**. The different delay update groups may apply delay increments or decrements at various intervals or magnitudes.

FIG. **8** shows an exemplary delay profile for five elements within a SAP with delay changes over time for each delay update group, e.g., A, B, C, D and E. In particular, plotline (a) illustrates an initial delay applied to delay elements for each of the transducer elements associated with the SAP, resulting in a flat profile and a signal directed straight at a focal point. As long as the relative delay between delay elements stays constant, the SAP maintains a static focus which generally does not change. The initial SAP focus can be determined by Δx and Δy steering parameters, which specify the delay slope in the x and y directions. Relative delays in the SAP can be updated at regular intervals by the SAP such that the focus direction of the SAP is changed. The time period for applying the delay updates can be, e.g., approximately 500 nanosecond steps.

Plotline (b) illustrates an exemplary final delay profile after all delay updates have finished. In particular, plotline (b) illustrates a gradual transition from the initial delay profile to a far field profile as the sub-aperture processor applies the delay updates at regular intervals to the ultrasound signals associated with the grouped transducer elements. As would be understood by those of ordinary skill in the art, by applying the delay updates to the ultrasound signals, the ultrasound signals received can be substantially aligned in phase for each of the dynamic delay update groups. As the delay updates are applied to the ultrasound signals, the steer/focal direction for the SAP can be moved. In this exemplary case, the delays for transducer elements in groups A and E are incremented and decremented at twice the rate, or twice the magnitude, of the transducer elements in groups B and D. The delays for transducer elements in group C remain static.

FIG. **9** shows how an exemplary delay profile works in conjunction with the dynamic delay update groups **204**, i.e., groups A, B, C, D and E. At time 0 (point **1**), the beam starts. At point **2**, the dynamical delay update increments start and can be applied to the ultrasound signals of the transducer elements **202** based on the group **204** assignment. Although the magnitude of the delay updates remains constant, the rate at which the delay updates are applied can be varied by changing the update rate for each group **204**. In some embodiments, the delay updates may be applied at the same rate while using two or more different delay update magnitudes. Ideally, the delays associated with each transducer element will change smoothly or gradually over time. However, these ideal delay curves can be effectively approximated in a simple manner with a certain number of quantized delay update steps. In the exemplary delay profile approximation shown in FIG. **9**, it should be understood that curves (a)', (b)', (c)', (d)' and (e)' are the exemplary ideal element delays. Curves (a), (b), (c), (d) and (e) are the corresponding quantized element delays. In particular, curve (a) for group A approximates the ideally desired curve (a)', curve (b) for group B approximates curve (b)', curve (d) for group D approximates curve (d)', curve (e) for group E approximates curve (e)', and curve (c) for group C remains constant. While groups A and E receive delay updates from the sub-aperture processor based on a rate counter at, e.g., 500 nanosecond intervals, the rate counter can apply the delay updates to groups B and D at 1000 nanosecond intervals, half the rate of groups A and E. Further, groups A and E receive delay updates in opposite directions, i.e., a +20 nanosecond update for each increment and a −20

nanosecond update for each decrement, respectively. Similarly, groups B and D receive delay updates in opposite directions. Meanwhile, group C remains static with no change in the delay signal. At point **3**, the dynamic updates can be stopped and, as can be seen from FIG. **9**, at time n, the dynamic focus of the exemplary ultrasound probe substantially aligns the ultrasound signals received by the transducer elements in phase for each of the dynamic delay update groups. Residual beamforming errors from point **3** and onward are demonstrated to be small and of little significance.

In some exemplary embodiments, an ideal delay profile for an ultrasound signal received by a transducer element can generally be approximated with a simple piecewise linear approximation with three segments. During the first segment of time, the initial delay remains static. During the second segment, delay updates begin and effectively approximate a certain delay update rate over time. During the third segment, the delay updates cease and delays remain static for the remainder of the receive period. The timing for these segments may be accomplished simply with three counters, e.g., a START counter, a RATE counter, and a STOP counter. For example, at point **1**, the sub-aperture processor can apply an initial delay profile, i.e., an initial depth, to the transducer elements, which remains constant for a period of time specified by a start counter. Once the start counter has reached a specified value at point **2**, the delays within the sub-aperture processor can be updated according to the groups with which they are associated. In particular, the delay updates can be incremented at some multiple of a rate counter, which determines the time between updates, thereby controlling the slope of the delay profile updates. The application of the delay updates can be seen in FIG. **9** as the steps which approximate the ideal delay profile plotline. Between points **2** and **3**, i.e., a mid field position, the approximation delay updates can be seen to more closely track the ideal delay profile. The number of delay updates can be counted by a stop counter and, at point **3**, i.e., the stop depth, the approximation delay updates are stopped by the sub-aperture processor. The delays for the transducer elements will thereby remain constant for the remainder of the receive period for the beam.

An optimal sub-aperture processor steering/focusing direction will change with depth. Ideally, the sub-aperture processor delay profiles can update along the receive beam to be ideally steered for every depth of interest. The desired delay updates can be calculated by subtracting the ideal near-field or initial delay profile form the ideal far-field delay profile. The residual delay pattern is the sum of the desired dynamic delay updates which should be applied gradually as the depth of focus increases, such that the sub-aperture processor steering tracks the desired focal point dynamically.

The preferred delay update group pattern, or rotary axis, can be determined by the delay updates required in the x and y directions. Each rotary axis requires some switches in the ASIC. To keep the complexity low, it is desirable to use a limited number of rotary axes. In some exemplary embodiments, 16 rotary axes provide 22.5 degree SAP steering resolution. In other exemplary embodiments, 8 rotary axes provide 45 degree steering resolution.

Once the rotary axis is determined, the direction that each delay update will apply to the transducer elements within the SAP is known. However, the number of updates and the timing of those updates must be determined. In some exemplary embodiments, the start, update and stop counters are determined by minimizing the mean delay error with respect to ideal dynamical delays for the elements in question.

The exemplary probe thereby approximates the delay curve with a piece-wise linear approximation, i.e., an initial static period, followed by one or more constant update rate periods, followed by another static period in the far-field. The magnitude of the delay updates and/or update rates/frequencies can be different based on the group **204** being delayed. In particular, although the magnitude of the delay updates can remain constant, the time period between updates may be adjusted for each group **204** to change the slope of the delay updates. In an alternative embodiment, the delay curve approximation can be non-linear to better resemble the ideal dynamical focusing delays or may include additional piecewise linear segments.

FIG. **10** shows an exemplary block diagram of a delay update timing controller **250** that can be implemented within each of the SAPs (e.g., SAPs **48**). With respect to FIG. **10**, the controller **250** can include and regulate at least one counter, e.g., a start counter **252**, a stop counter **254**, a rate counter **256**, and the like, for regulating the timing of the piecewise linear approximation of the delay updates. In some exemplary embodiments, one counter can act as the start counter **252**, the stop counter **254**, and the rate counter **256**. In some exemplary embodiments, separate counters can be implemented to perform the functions of the start counter **252**, the stop counter **254**, and the rate counter **256**. The controller **250** can apply an initial delay profile to the delay elements (e.g., delay elements **46**) associated with each of the transducer elements **202**, which remains constant for a period of time specified by the start counter **252**. Once the start counter **252** reaches a specified value, e.g., a value predetermined by the controller **250**, or counts down from a specified value to 0, the delay within the delay elements of the sub-aperture processor can be updated according to the groups **204** to which the transducer elements **202** are assigned. In one exemplary embodiment, some groups **204** can be incremented, some groups **204** can be decremented, and/or some groups **204** can remain static.

The delay updates can be incremented at some multiple (or factor/fraction) of the rate counter **256**, which determines the time between updates. Thus, the magnitude of the delay may differ from one group **204** to the next, e.g., some delay elements can be updated at twice (or half) the rate or with twice (or half) the magnitude as compared to other delay elements **202**. For example, based on the rate counter **256**, delay updates can be applied at 100 nanosecond periods for groups A and E, 200 nanosecond periods for groups B and D, and not applied for group C. Thus, if a delay update magnitude is 1.0, group A can receive a delay increment of +1.0, group E can receive a delay increment of –1.0, group B can receive a delay increment of +0.5, group D can receive a delay increment of –0.5, and group C can receive a static delay, i.e., the signal would remain the same. In particular, in one embodiment, for one beam, groups A and B can receive a delay modification in one direction and groups D and E can receive a delay modification in the opposite direction. The number of updates can further be governed by the stop counter **254**. The stop counter **254** may count the number of desired delay updates and, when the stop counter **254** reaches a specified value, e.g., a value predetermined by the controller **250**, dynamic delay updates can be stopped by the sub-aperture processor. Once the delay updates are stopped, the delays for the delay elements associated with each of the transducer elements **202** can remain constant for the remainder of the beam receive period.

The assignment of dynamic delay update groups **204**, the magnitude of the initial delay, and/or the magnitude of the delay updates can be reevaluated and reassigned by the controller **250** of the sub-aperture processor for each beam. Thus, the initial delay profile can be defined by the desired steering of the beam and can be updated for each beam, while the

dynamic delay updates profile can be varied over time for each beam. The sub-aperture processor can further sum the ultrasound signals of all the transducer elements **202** of the SA (e.g., SA **42**, **200**) and implement one channel as an output of the SAP for the entire SA that can be communicated to the main processing unit external to the probe. Thus, for example, rather than implementing 25 channels for a 5×5 SA, one channel can be used, thereby reducing the number of cables or wires extending between the ultrasound probe and the main processing unit. Utilizing the piecewise linear approximation for the delays and subsequently combining the phase aligned signals into a single channel for each sub-aperture can significantly reduce the complexity for implementing a dynamic beamformer and may reduce the silicon area required. If the total circuitry needed for an element is less than or approximately equal to the size of the transducer element, the ASIC may be placed directly behind the transducer stack. The reduced silicon area can also be advantageous for the signal processing and power requirements of the ultrasound probe.

With reference to FIG. **11**, an exemplary steering plot is illustrated for two SAPs at different positions on the aperture shown in FIG. **4**. In particular, a SAP near the edge of the array of transducer elements is represented by piecewise linear curve (a) and approximated by curve (a)' and a SAP near the center of the array of transducer elements is represented by curve (b) and approximated by curve (b)'. As described above, an initial delay is applied during time period A to each SAP until a specified value is reached by the start counter **252**. The delay update approximation is then applied during time period B to each SAP based on a rate determined by a rate counter **256**. Once a specified number of delay updates have been reached at time period C, the stop counter **254** can stop the delay updates and a static delay remains for the remainder of the beam.

While exemplary embodiments have been described herein, it is expressly noted that these embodiments should not be construed as limiting, but rather that additions and modifications to what is expressly described herein also are included within the scope of the invention. Moreover, it is to be understood that the features of the various embodiments described herein are not mutually exclusive and can exist in various combinations and permutations, even if such combinations or permutations are not made express herein, without departing from the spirit and scope of the invention.

The invention claimed is:

1. An ultrasound probe with sub-aperture processing capable of dynamic focus, comprising:

an array of transducer elements that forms a sub-aperture in the ultrasound probe, wherein the transducer elements of the sub-aperture are configured to receive ultrasound signals, and wherein the transducer elements of the sub-aperture are divided into a plurality of dynamic delay update groups comprising at least a first group of transducer elements and a second group of transducer elements;

a sub-aperture processor configured to:

apply an initial delay to the transducer elements of the sub-aperture; and

dynamically apply delay updates to the ultrasound signals associated with the transducer elements of the sub-aperture, wherein the delay updates are applied to the ultrasound signals repeatedly for a predetermined time period to approximate an ideal delay profile, and wherein a magnitude of the delay updates is dependent on the dynamic delay update groups.

2. The ultrasound probe of claim **1**, wherein the sub-aperture processor is configured to:

apply a first delay modification to the first group of transducer elements within the sub-aperture; and

apply a second delay modification to the second group of transducer elements within the sub-aperture, wherein the first delay modification is different from the second delay modification.

3. The ultrasound probe of claim **2**, wherein the first delay modification and the second delay modification are applied in different directions as a delay increment or a delay decrement.

4. The ultrasound probe of claim **2**, wherein the dynamic delay update groups within the sub-aperture are updated at two or more different rates.

5. The ultrasound probe of claim **1**, wherein the delay updates are a piecewise linear approximation of the ideal delay profile associated with the transducer elements in the dynamic delay update groups.

6. The ultrasound probe of claim **1**, wherein the transducer elements of the sub-aperture are configured to transmit ultrasound signals, and wherein the sub-aperture processor is configured to apply the initial delay to the ultrasound signals to specify a focal point of the ultrasound signals.

7. The ultrasound probe of claim **1**, wherein the sub-aperture processor is configured to apply the delay updates to the ultrasound signals to substantially align the ultrasound signals received by the transducer elements in phase for each of the dynamic delay update groups.

8. The ultrasound probe of claim **1**, wherein the sub-aperture processor is configured to process a first beam with a first set of dynamic delay update parameters and a second beam with a second set of dynamic delay update parameters, and wherein the first set of dynamic delay update parameters are different from the second set of dynamic delay update parameters.

9. The ultrasound probe of claim **1**, wherein the sub-aperture processor is configured to set a rate for applying discrete delay updates to the ultrasound signals associated with the transducer elements of the sub-aperture.

10. The ultrasound probe of claim **1**, wherein the sub-aperture processor is configured to set a magnitude of the initial delay applied to the ultrasound signals associated with the transducer elements of the sub-aperture.

11. The ultrasound probe of claim **1**, wherein the delay updates are one of an incremented delay, a static delay, or a decremented delay.

12. The ultrasound probe of claim **1**, wherein the sub-aperture processor is configured to apply a set of initial delays to the ultrasound signals associated with the transducer elements of the sub-aperture, begin applying the delay updates to the ultrasound signals associated with the transducer elements of the sub-aperture in response to a start counter, continue applying the delay updates at intervals specified by a rate counter, and stop applying the delay updates to the ultrasound signals associated with the transducer elements of the sub-aperture in response to a stop counter.

13. An ultrasound system with a dynamic focus, comprising:

an ultrasound probe comprising an array of transducer elements that form a sub-aperture, wherein the transducer elements of the sub-aperture are configured to receive ultrasound signals, and wherein the transducer elements of the sub-aperture are divided into a plurality of dynamic delay update groups comprising at least a first group of transducer elements and a second group of transducer elements;

a sub-aperture processor configured to:

apply an initial delay to the transducer elements of the sub-aperture; and

dynamically apply delay updates to the ultrasound signals associated with the transducer elements of the sub-aperture, wherein the delay updates are applied to the ultrasound signals repeatedly for a predetermined time period to approximate an ideal delay profile, and wherein a magnitude of the delay updates is dependent on the dynamic delay update groups.

14. The ultrasound system of claim **13**, wherein the sub-aperture processor comprises at least one counter.

15. The ultrasound system of claim **14**, wherein the sub-aperture processor is configured to apply the initial delay to ultrasound signals associated with the transducer elements, apply the delay updates in response to the at least one counter, apply discrete delay updates to the ultrasound signals associated with the transducer elements at a specified rate each time the at least one counter reaches a specified value, and stop the delay updates after completing a specified number of delay updates has been completed.

16. A method of receiving ultrasound signals with a dynamic focus, comprising:

applying an initial delay to ultrasound signals associated with transducer elements of a sub-aperture disposed in an ultrasound probe;

dividing the transducer elements of the sub-aperture into a plurality of dynamic delay update groups comprising at least a first group of transducer elements and a second group of transducer elements; and

applying delay updates to the ultrasound signals associated with the transducer elements of the sub-aperture, wherein the delay updates are applied to the ultrasound signals repeatedly for a predetermined time period to

approximate an ideal delay profile, and wherein a magnitude of the delay updates is dependent on the dynamic delay update groups.

17. The method of claim **16**, further comprising transmitting the ultrasound signals via the transducer elements of the sub-aperture and applying the initial delay to the ultrasound signals via a sub-aperture processor to specify a focal point of the ultrasound signals.

18. The method of claim **16**, further comprising receiving the ultrasound signals via the transducer elements of the sub-aperture and applying the delay updates to the ultrasound signals via a sub-aperture processor to substantially align the ultrasound signals received by the transducer elements in phase for each of the dynamic delay update groups.

19. The method of claim **16**, further comprising processing a first beam using a first set of dynamic delay update parameters and a second beam using a second set of dynamic delay update parameters, wherein the first set of dynamic delay update parameters are different from the second set of dynamic delay update parameters.

20. The method of claim **19**, further comprising applying different delay increments or decrements for the delay updates for each of the first and second sets of dynamic delay update parameters.

21. The method of claim **19**, further comprising applying different delay update periods for the delay updates for each of the first and second sets of dynamic delay update parameters.

22. The method of claim **19**, further comprising setting a rate for discretely applying the delay updates to the ultrasound signals associated with the transducer elements of the sub-aperture.

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